Economic effects of renewable energy expansion: A model-based analysis for Germany

Jürgen Blazejczak [a], Frauke G. Braun [b,1], Dietmar Edler [a], Wolf-Peter Schill [a,*]

[a] DIW Berlin, Mohrenstraße 58, 10117 Berlin, Germany
[b] DIW Berlin at the time of writing, now Federal Ministry for Economic Affairs and Energy, Berlin, Germany

A B S T R A C T

The increasing utilization of renewable energy sources (RES) is a major energy policy strategy in many countries worldwide. Germany is a forerunner in the deployment of RES and has ambitious goals for the future. The support and use of renewables affects the economy: It creates business opportunities in sectors producing renewable energy facilities, but comes with costs related to supporting its deployment. This paper analyses and quantifies the net balance of economic effects associated with renewable energy deployment in Germany until 2030. To this end, we use a novel model, the 'Sectoral Energy-Economic Econometric Model'. This is an econometric multi-country model which, for Germany, contains a detailed representation of industries, including 14 renewable energy technology sectors. Our results show that renewable energy expansion can be achieved without compromising growth or employment. The analysis reveals a positive net effect on economic growth in Germany. Net employment effects are small, but also positive. Their size depends strongly on labour market conditions and policies. Results at the industry level indicate the size and direction of the need for restructuring across the sectors of the Germany economy.

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* Corresponding author. Tel.: +49 30 89789 675; fax: +49 30 89789 113.
  E-mail address: wschill@diw.de (W.-P. Schill).
  [1] Opinions expressed in this article are those of the author and do not necessarily reflect views of the institution.

1. Introduction

With increasing awareness for the risks of climate change, many countries have endorsed strategies for a transition to low carbon economies. A major decarbonisation strategy is to

substitute fossil power generation with renewable energy sources [37]. This provides environmental and climate benefits including lower emissions of CO_2 and other air pollutants. Decarbonization may also have favourable economic impacts—for instance by creating opportunities in manufacturing and services. Realizing such economic potentials has become an additional rationale for climate change policies such as the 'Green Growth Strategy', which was initiated by the OECD in 2009 to boost economic recovery within a green framework for long-term sustainable growth [45].

The social acceptance of locally deployed renewable energy sources (RES) can be very high due to the public perception of their environmental and economic benefits ([1,55]. It is, however, clear that these do not come without costs. In particular, utilising RES incurs additional upfront investments compared to other power generation technologies, and may substitute income and jobs in the conventional energy industry. The balance of economic benefits and costs, that is, the net economic impact, of renewable energy deployment is still disputed. Therefore, analyses of these net economic impacts are needed to fill this research gap and to improve upon the design and acceptance of renewable energy policies.

In this article, we examine and quantify the net aggregate economic effects as well as sectoral implications of German renewable energy support using scenario calculations with a novel model, the 'Sectoral Energy-Economic Econometric Model' (SEEEM) for Germany. It provides insights on, first, the macro-economic impacts and, second, structural effects across the sectors of the economy. We focus on the case of Germany, which is a leader in supporting renewables. As many countries have followed the German example, our analysis can generate meaningful insights that apply to other countries as well.

There is no consensus in the literature as to the direction and size of the macroeconomic effects of the deployment of renewable energy technologies. The OECD [46] compares a number of studies of the economic impacts of mitigation policies in various countries. In most cases, it finds small negative impacts on GDP and employment. The magnitude of effects crucially depends on assumptions about labour market flexibility. A number of important factors determining employment outcomes of such model analyses have been suggested by Lambert and Silva [39], among them different assumptions on the labour intensity of renewables and cost developments. More generally, Walz [59] has grouped factors determining the macroeconomic effects of RES into four cate-gories: costs and price effects, structural effects, multiplier and accelerator effects and innovation dynamics. The OECD [46] has conducted simulations of mitigation policies with its ENV-Linkages model, a general equilibrium model which focuses on costs and price effects but neglects innovation dynamics. The results suggest that such policies have a small negative impact on growth with net job losses somewhat more pronounced. Positive employment effects arise only if revenues from an emission trading scheme are redistributed to reduce labour taxation. Böh-ringer et al. [10] reach comparable conclusions using a similar model for Germany. In doing so, they do not consider productivity gains as a source of additional production or possible improve-ments of non-price international competitiveness. Walz [59] has emphasised the importance of innovation dynamics, resulting cost savings and additional exports. He concludes from the analysis of patent data that innovation dynamics are above average for renewable energies.

The analysis presented in this article is designed to capture the multiple interacting and counterbalancing mechanisms which determine the overall economic impact of increasing the contribu-tion of renewables to energy. The deployment of renewables promotes innovation, facilitates the development of a green technology sector and creates new markets. Activities in other sectors of the economy can also benefit through inter-industry relations, such as the supply of intermediate inputs or
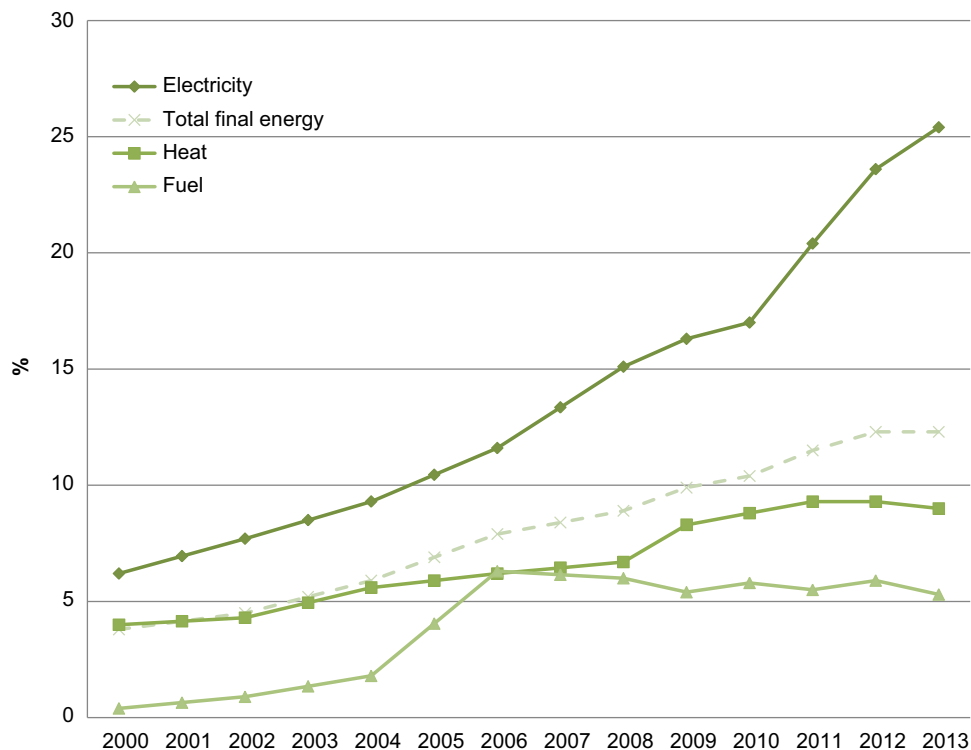

Fig. 1. Renewable energy shares in final energy consumption in Germany. Electricity generation from renewable sources related to gross power consumption. Renewable heat supply related to total final heat demand. Renewable fuel supply related to fuel demand in road transportation until 2002, and related to total fuel demand excluding aviation from 2003 on.
Sources: BMWi [9].

manufacturing equipment. Further, drawing on domestic renewable energy sources decreases importation of fossil fuels. On the other hand, investment and employment in the conventional energy industry is displaced. Due to additional costs, renewables still depend on policy support, which typically translates into higher energy prices. Higher energy prices may work as a drain to energy users' budgets and hurt the competitiveness of energy-intensive industries, which leads to a contraction of economic activity in terms of lower consumption and profit or investment [2].

Importantly, these developments will trigger second-order effects that affect not just employment and growth of the overall economy, but also the relative importance of various sectors, i.e. the sectoral structure of the economy. Due to different income elasticities of demand, for example, the budget effect will influence production differently by sector. Likewise, increasing energy prices will primarily hurt energy intensive industries. The induced restructuring processes may be costly in terms of reallocations of resources or retraining of workers. It should be stressed that structural change is an ongoing process in an economy and that the induced structural change in the context of decarbonisation strategies comes along with additional risks as well as opportunities. Hence, in order to fully assess the impact of decarbonisation strategies on the economy, the analysis needs to account for the interrelated and counterbalancing effects in an economic system and needs to go beyond the aggregate level and provide insights on sectoral effects in the economy.

The analysis applies the model SEEEM to evaluate and compare different scenarios for the expansion of renewables in Germany through 2030. SEEEM is an econometric multi-country model that, in the case of Germany, contains a detailed representation of economic sectors, including such for renewable energy technologies. It fully accounts for feedback relations between various macroeconomic and sectoral variables as well as across time and countries to draw a balance of the countervailing dynamics—that is to obtain net effects.

The remainder of this article is structured as follows: The subsequent section describes the development of renewable energy and its support framework in Germany. Moreover, it provides an overview of the relevant literature on economic impacts of renewable energy deployment. Section 3 introduces the analytical framework by describing the structure and characteristics of the model SEEEM and the scenarios developed. Results of the scenario runs are presented in Section 4. The final section concludes.

2. Renewable energy expansion and the economy

In recent years, the use of RES, like wind, solar, biomass and hydro, has increased substantially worldwide. For example, global installed wind capacity increased from 6.1 GW in 1996 to 318 GW in 2013, while global solar photovoltaic capacity grew from 0.7 GW to 139 GW over the same period of time. Total yearly investment into renewable energy technologies rose from US$40 billion in 2004 to US$279 billion in 2011 and slightly decreased again to US$214 billion in 2013 REN21 [50]. In coming decades, further large-scale deployment of RES technologies is expected in many countries. In IEA's recent 'New Policies Scenario', investments in the power sector are dominated by capacity additions of renewable technologies. Between 2014 and 2035, cumulative global renewable investments of US$5.9 trillion are projected [36]. The European Union aims to increase the share of renewable energy in final energy consumption to 20% by 2020 [30], and to 27% by 2030 [31], which implies even larger shares in power generation.

Fig. 1 shows the growing shares of renewable energy in final energy consumption in Germany between 2000 and 2013. The share in total final energy consumption increased from around 4% in 2000 to more than 12% by 2013. The growth in the power sector is particularly strong. The share of renewable energy in gross electricity consumption rose from around 6% in 2000 to over 25% by 2013. In 2000, hydro power accounted for the largest part of renewable generation (60%). Wind power (26%) and biomass (13%) played minor roles, while photovoltaics were virtually absent [9]. This changed dramatically by 2013, with wind power providing 35%, biomass 31% and hydro power only 14% of renewable power generation. Solar PV, which had the largest growth rate, accounted for around 20% in 2013 [9]. In the future, further large-scale deployment of renewable generation capacity is planned in Germany, such that the power sector could be mainly based on RES in the long run. According to the government's Energy Concept of 2010, renewables should supply 35% of gross electricity consumption by 2020, 50% by 2030 and 80% by 2050 [7].

The renewable energy boom in Germany was triggered by supportive policies. Renewable energy utilization for heating is encouraged through ordinances, investment grants, low-interest loans and other market incentive programs [51]. The use of biofuels is promoted by quotas. As for electric power, a feed-in tariff for RES technologies was first introduced by the *Stromein-speisungsgesetz*, which came into force in 1991 [13]. It granted priority feed-in for renewable energy sources and a guaranteed minimum price. In 2000, it was replaced by the *Erneuerbare-Energien-Gesetz* (EEG, Renewable Energy Sources Act), which made investments into solar power and biogas more attractive [14]. The differential costs between the feed-in tariff and the market price are apportioned among power consumers. Importantly, the guaranteed tariffs for new installations are designed to decrease over time. This degression aims to phase out support over time and to gradually integrate RES generators into the liberalised market. Subsequently, the EEG was regularly amended in order to adjust tariffs to reflect technologic and market developments [15–17]. Tariffs generally depend on generation technology and on plant size. In addition, several bonuses were granted, for example for small biomass plants or for wind repowering. The EEG has proven to be very effective regarding RES deployment as illustrated in Fig. 1 [9,12,18].

The growing utilization of renewable energy sources comes along with increasing economic activity in the renewable energy sectors. Among the existing studies on the economic effects associated with renewable energy expansion, many focus on the assessment of the additional growth and, particularly, employment created. The *gross* employment effect is always positive. Depending on the type and coverage of analysis it can be further distinguished to include, first, persons *directly* employed in manufacturing, operating and maintaining renewable energy installations and supplying biofuels and biomass. Second, gross employment also includes persons *indirectly* employed along the value chains of the sectors directly providing final demand. For example, manufacturing of solar panels requires inputs from other sectors such as electronics [5,60].

Studies focussing on gross employment effects have been conducted for several countries and renewable energy technologies, including Germany [40,5], the UK [29], Greece [56], the EU [4,49], the Middle East [58], Brazil [54], and the U.S. [38,60]. Methodologically these studies use surveys (e.g. [4]); employment factors[2] like the number of persons required to manufacture, install and operate a MW of a facility [60,29,43]; input–output

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[2] Llera et al. [43] develop an analytical model that captures different employment intensities along the supply chain of the Spanish PV industry.

analysis as well as combinations of these approaches [5,40,56]. Calculations for Germany indicate that direct and indirect gross employment for renewables amounted to 371,400 persons in 2013 [48]. This result is based on input–output analysis and encompasses the employment effects of investment, exports, operation and maintenance as well as the production of biomass and biofuel Frondel et al. [33] aim to evaluate gross impacts of German renewable energy expansion without using model calculations.

Few studies go beyond the determination of gross effects following a *net* approach that includes amplifying as well as countervailing mechanisms and drivers. Such analyses require a sophisticated model of economic interdependencies in order to account for growth, income and jobs eliminated by renewable expansion. Dixon et al. [28] in a study on biomass substitution for petroleum override the usual assumption in general equilibrium models that wages adjust in a way that full employment is achieved. Arguing that increased labour force participation occurs in the agricultural sector they find positive effects on GDP and net employment. Using a model of essentially Keynesian logic, i.e., focusing on multiplier and accelerator effects, and incorporating innovation dynamics, a study by Cambridge Econometrics [19] compares electricity generation by offshore wind installations instead of gas turbines. Even without an increase in exports, GDP and employment are expected to be significantly higher in 2030 in case of large-scale offshore wind deployment. Sensitivity analyses show that the size of the impact on GDP crucially depends on the import content of offshore wind installations as well as offshore wind costs and gas prices.

As for the German 'Energiewende', the Boston Consulting Group [11] surveys a number of studies dealing with the macro-economic effects of the project. Net employment effects in 2030 are estimated to range between −70,000 and +329,000 by different studies, reflecting varying modelling assumptions with respect to exogenous impulses or economic mechanisms. In an earlier study, Hillebrand et al. [35] calculate a net balance of the expansive impacts due to the investment in RES-technologies and the contractive impacts in forms of higher energy costs in Germany between 2003 and 2010. In the initial years, the expansive investment effect dominates, while in later years the additional costs become stronger and the net employment effect turns negative. Lehr et al. [41,42] provide more recent net estimates for Germany. They use scenario calculations based on a combination of an econometric input–output model for Germany, an ecological model and a model for international linkages. According to these studies, net employment effects in 2030 are positive throughout all scenario versions. The largest job gain occurs in a scenario with high fossil fuel prices and strong exports of renewable energy technologies and components. Earlier calculations in Lehr et al. [40] also corroborate positive growth, consumption and employment effects.

3. Modelling approach

The net economic balance of the various effects associated with a renewable expansion strategy is obtained by applying model-based scenario analyses. We compare different runs of the SEEEM model: one with a scenario that describes a renewable energy expansion in Germany and another run with a counterfactual scenario without any renewable deployment (therefore coined NULL). Each scenario sets out from a consistent set of economic impulses, for instance investments in renewable energy technologies and additional costs, which are fed into SEEEM. The model calculates the responses of macroeconomic and sectoral variables to these exogenous stimuli.

Among the basic approaches to examine linkages between the economy and energy policies – top-down and bottom-up models –
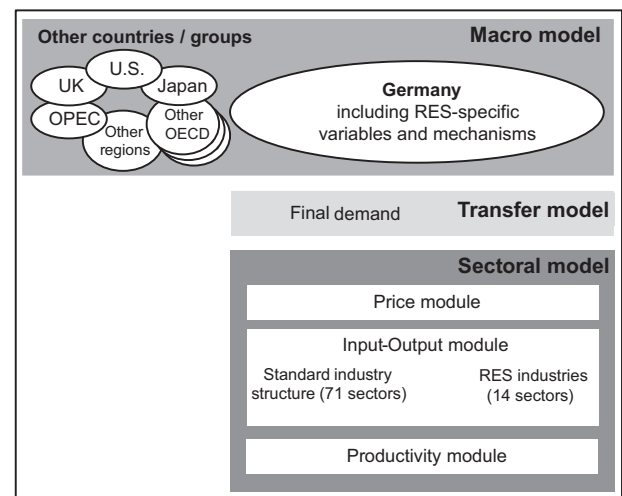

Fig. 2. Model structure of SEEEM.

SEEEM is a top-down model. Top-down models focus on feedback and price effects within an economy and, importantly, economic interactions occurring via international markets such as trade in goods and services. Bottom-up energy-economic models, on the other hand, feature a detailed representation of energy demand and supply, including different energy sources, carriers and conversion technologies, but are less sophisticated in modelling economic relations (compare [44,53]). In the following, we first describe the model structure and features of SEEEM and subsequently introduce the different scenarios considered.

3.1. The model SEEEM

3.1.1. The general framework

SEEEM is explicitly designed for the purpose of analysing the macroeconomic and sectoral effects of environmental policies. It is based on the well-established macroeconometric multi-country model NiGEM (National Institute Global Econometric Model).[3] Most OECD countries are represented with a full country model while smaller countries or blocks of countries, such as OPEC, are modelled in a more parsimonious manner. The country model for Germany in NiGEM is substantially modified and expanded to suit the needs of our research, in particular integrating a detailed sectoral module of the German economy following input–output approaches.

The core of SEEEM, NiGEM, is an economic model for purposes of policy simulations and forecasting. In contrast to other models, many settings such as monetary policy regimes or expectation formation can be easily changed.[4] NiGEM is firmly rooted in economic theory and state-of-the-art econometric techniques. The modelling approach can be considered as Neo-Keynesian with forward-looking agents and nominal rigidities, which slow the adjustment of the economy to external events. Economic relations are determined by identities and econometrically estimated behavioural equations. Dynamic error-corrections models are applied to specify relevant behavioural equations; those model variables accordingly adjust only gradually to equilibrium after a shock.
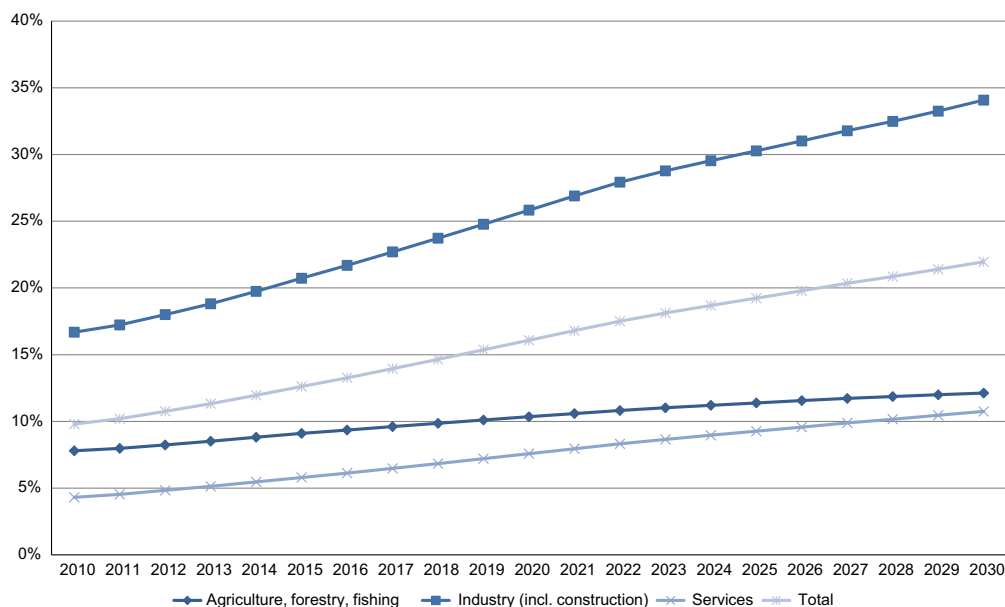
Fig. 3. Imported intermediate goods and services as share of gross production by main sectors, illustrated for the EXP scenario.

The macro model is a complete representation of the economy in the sense that it covers production, government activities, income generation and consumption, prices, wages, exchange rates, and international financial and trade flows. For our research we modified and augmented the German model in NiGEM at the macro level and expanded it to include a sectoral module. It now accounts for second-round effects at the macro-level and across countries, horizontal linkages between sectors and for feedbacks between the macro and sectoral level for Germany.

3.1.2. The sectoral model for Germany

Important economic drivers related to renewable energy expansion are the investment effect and the operation and maintenance (O&M) effect. RES facilities investments and O&M expenditures increase aggregate final demand, which, depending on the technology considered, may benefit different production and employment of particular sectors. In order to assess such impacts at both aggregate and sectoral levels, as well as to analyse the sectoral dimension of macro-level effects that are, for instance, triggered by additional costs to consumers, we introduce a sectoral module for Germany and link it to the macro model through a transfer model (Fig. 2). This determines the final demand components in such a way that they are consistent with the accounting concepts of input–output tables.

The sectoral model computes key variables, including gross output, gross value added and employment. The contribution of each sector to final demand and imported intermediates is a required input for this. We use annual data on the historic sectoral structure to obtain the final demand components, such as sectoral level private consumption, gross investment and exports ([20–27]). We assume the respective contribution of a sector to the respective final demand variable to be constant from the last year onwards for which data is available.

We estimate sectoral equations for imported intermediates, depending on past imported intermediates, total imports and a trend. Fig. 3 shows the development of imported intermediates relative to gross production.[5] It illustrates that international

linkages of the German economy intensify over time. International sourcing of intermediates is particularly strong in areas like industry (around 35% in 2030), while services remain more oriented towards the domestic side (around 10% in 2030).

The model includes an input–output table for each year of the analysis, derived from official statistics. The latest available input–output table is held constant for the subsequent years.[6] In addition to the 71 sectors represented in official statistics, we define and describe empirically 14 additional RES sectors. We distinguish seven renewable sources of energy (or technologies) in order to achieve a better degree of homogeneity of the underlying production processes:

1. wind,
2. photovoltaics,
3. solar thermal heat,
4. hydro,
5. biomass,
6. biogas, and
7. geothermal.

For each of these sources we define two new sectors: 'Production of RES facilities' and 'Operation and maintenance of systems for the use of RES'. Each of the 14 new sectors is defined as a new column in the input–output table, describing the input or cost structure, and a new row, describing the output or sales structure.[7] The new sectors are fully integrated into the input–output framework, e.g. they suffice the accounting scheme that the sum of inputs equals the sum of outputs for each sector. After integrating RES we end up with 85 sectors representing the structure of the German economy.

To determine employment we proceed as follows: Gross output is calculated, which has to be produced by each sector to satisfy

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[5] We present here for illustration purposes a path based on the EXP scenario, which is introduced in Section 3.2. The outcomes of other scenarios are very similar.

[6] The model is designed in a way that input-output tables can be modified in order to reflect expected structural changes in the inter-industry linkages. This feature is not exploited in this article. It should be noted that the model analysis draws on differences between scenarios, such that parameter assumptions which are identical in both scenarios cancel out.

[7] For details of the empirical foundation and the methods involved see Lehr et al. [42]. For a previous study see Lehr et al. [40].

final demand (derived as explained above), using the Leontieff inverse. The share of gross value added in gross production is determined based on past relations. Gross value added is deflated by prices derived from econometric equations involving the past relation of sectoral to aggregate prices (Price module). Sectoral price data are obtained from EUKLEMS [32]. Productivity links real gross value added to hours worked in each sector. Productivity trends are estimated with past relations of sectoral to aggregate productivity as explanatory variables (Productivity module). A corresponding specification is used to estimate average hours per worker. Hours worked to average hours per worker yield employment.

A different approach is used for the newly defined RES sectors. Deriving empirical results from Lehr et al. [42] we calculate employment in the RES sectors by using sectoral labour coefficients, i.e., labour input per unit of gross output. Over time labour coefficients represent learning curve effects in the expanding RES sectors and are at the same time also influenced by labour productivity trends in the rest of the economy.

3.1.3. RES-specific macro model mechanisms

In addition to sectoral effects discussed above, the macroeconomic effects related to RES expansion are considered in the Macro model. The investment variable in the German Macro model is split into a variable representing renewable investment (an aggregate of the sectoral investment variables for seven renewable energy technologies), a variable for all other investments, and a variable that considers displaced investments in nonrenewable energy technologies. These variables are fed with exogenous scenario information during simulations.

Additional costs of RES constrain the budget available for the purchase of non-energy goods or services. This repercussion is termed as 'budget effect' in the literature (e.g. [40]), though not all analyses of the economic effects of renewable energy promotion account for this (e.g. [60]). The budget effect is considered in SEEEM in the way that consumers fully bear the burden of additional costs. Consumers cover these costs either directly via feed-in tariff attributions or indirectly via increasing prices of goods and services.

Trade is another important channel through which the expansion of renewables affects a country's economy. First, a wider penetration of renewables reduces the demand for conventional energy, which, in the case of Germany, is imported to a large degree. In 2010, around 71% of Germany's primary energy demand was met by imports [8]. This number is mainly driven by high import shares of oil, natural gas and hard coal. Second, lead-market research indicates that decarbonizing the economy promotes innovation and facilitates the development of a green technology sector (e.g. [3]). It thus creates competitive advantages in international markets (innovation and trade effects). Although such trade effects are an important aspect in the context of renewable energy expansion, several studies fail to include these (e.g. [35,60]). Additional exports of RES facilities and components are covered by specific variables in SEEEM's export equation. The German import equation considers imported RES facilities and substituted imports of fossil fuels.

3.2. Scenarios

We analyse the economic effects of renewable energy expansion in Germany between 2000 and 2030. A renewable energy expansion scenario (EXP) is compared to a counterfactual NULL scenario, in which no renewable energy deployment takes place throughout the entire period of investigation. Taking differences between the model outcomes for EXP and NULL allows

determining the economic net effects of renewable energy deployment in Germany. Renewable expansion in other countries is not explicitly modelled, but implicitly represented in the form of German exports of RES facilities and components.

Up to 2010, the expansion scenario represents historic data. From 2011 onwards, it follows the *Leitstudie 2011* [6].[8] This has been conducted on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and serves as a guideline scenario for the development of renewable energy which is often used in energy-economic studies. According to the reference scenario of this study (2011 A), renewable energy will cover 63% of gross electricity consumption, 29% of final heat consumption and 20% of final fuel consumption by 2030. This scenario includes both diminished imports of fossil fuels and additional costs associated with RES expansion. Aside from domestic renewable expansion, exports of RES facilities and components are also considered.

Fig. 4 depicts the paths of these economic impulses for the expansion scenario from 2000 to 2030. In contrast, all stimuli are zero in the NULL scenario. The impulses include investments, O&M costs, demand for biomass and biofuels, and exports of RES facilities and components. RES exports are estimated according to BMU [5]. We only include investments, O&M costs and exports from domestic production. Further impulses consist of displaced investments in conventional energy technologies, substituted imports of fossil fuels and additional costs. According to BMU [6], additional costs will decrease after 2015 due to learning curve effects and price increases of conventional fuels; after 2025, these factors cause the additional costs to become negative.[9] Thus, renewable energy expansion is – in the long run – assumed to incur even lower costs than conventional energy supply.

To assess the robustness of our model outcomes, we carry out two sensitivity analyses with respect to cost and price effects and alternative labour market conditions. In the basic EXP run, we assume that the additional costs related to renewable energy expansion do not have a major impact on unit costs of German producers. This assumption appears justified, because industries that face international competition are largely exempted from financial burdens related to the support of renewables. For example, energy-intensive industries bear only a small part of feed-in apportionments. Notwithstanding, renewable energy expansion may still trigger a price-wage spiral via increasing energy prices, which may lead to increasing unit costs and harm the price competitiveness of the German economy. We thus carry out a sensitivity analysis named COST, in which additional RES costs lead to increasing unit costs.

Secondly, we test the model's sensitivity with respect to labour market flexibility. The model is adjusted to allow for a lower rate of natural unemployment, such that additional economic growth goes along with a stronger increase of employment in Germany. Accordingly, the FLEX sensitivity run simulates the effects of an additional activation of unemployed persons, supported for example by retraining measures. Importantly, economic stimuli in both sensitivity analyses are the same as in the EXP scenario (Fig. 4).

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[8] The study develops comprehensive scenarios that achieve the targets of the German government's energy concept. Due to a serious of precursor studies, it is often termed 'Leitstudie' (or Lead Study), although this is not the official name. A follow-up study was commissioned in 2013, the results of which are not yet available.

[9] BMU [6] which we draw upon in this research project, underestimates the strong deployment of photovoltaics that took place in 2012. Compared to the assumptions of the study, both photovoltaic investments and additional costs of renewable energy generation have increased. That is, both positive and negative economic stimuli tend to be somewhat higher than modelled here.
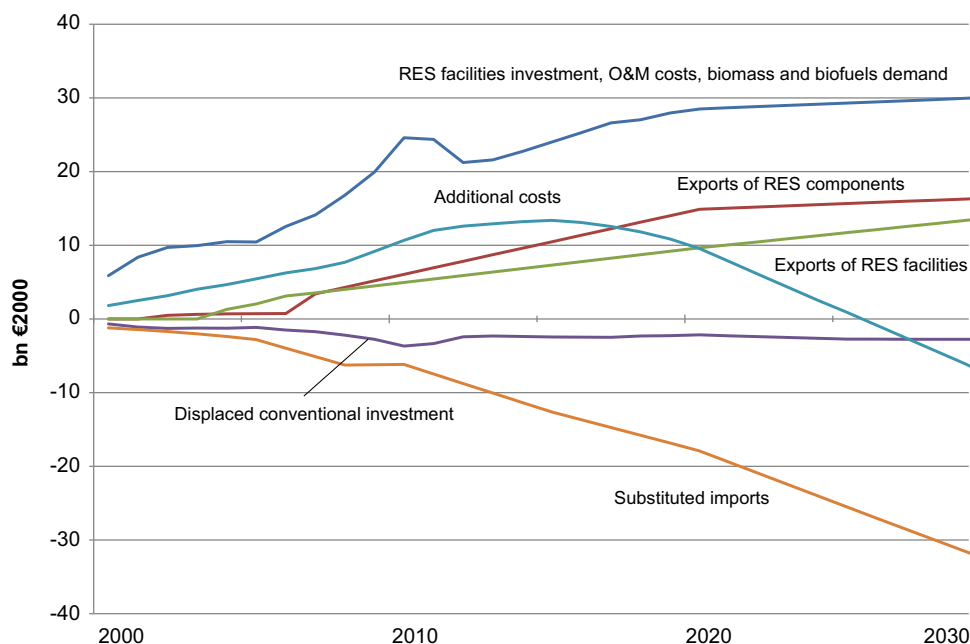
Fig. 4. Economic stimuli of the expansion scenario (EXP) in billion euros, in constant prices of 2000. Investment, operating costs and exports relate to domestic production. Substituted imports refer to substituted imports of conventional energy carriers.
Sources: Calculations of DIW Berlin based on BMU [6].

Table 1
Net economic effects of RES expansion in Germany in the EXP scenario. Change between EXP and NULL in %, employment in absolute numbers.

	2010	2020	2030
GDP	**2.1**	**2.8**	**3.1**
Private consumption	1.1	2.2	3.7
Private investments	13.5	10.0	7.4
Exports	1.0	1.2	0.9
Imports	1.6	0.9	0.9
Productivity	**2.0**	**2.8**	**3.1**
Employment	**43,000**	**14,000**	**3,000**

GDP and final demand components in euros (constant prices of 2000). Productivity is calculated as GDP per person employed. Private investments without construction investments.

4. Results

4.1. The renewable energy expansion scenario (EXP)

Overall, the model results reveal that the deployment of renewables leads to positive net economic effects in Germany (Table 1). German GDP (in constant prices) will be 3.1% higher by 2030 in the expansion scenario compared to the NULL scenario. Correspondingly, the average annual GDP growth rate is by 0.1% higher in EXP during the period 2000 to 2030. The GDP difference between the two scenarios is mainly related to increased investment activities and higher private consumption.

The expansion of renewables requires, for example, investment in wind power plants or solar photovoltaic modules, which expand final demand and production. However, simultaneous investments in conventional infrastructure, such as coal-fired power plants or refineries, decrease relative to NULL, thus exerting a contractive effect, which, however, is smaller than the expansive RES investment impulse. Subsequently, further indirect dynamic effects are triggered not just on the macro-level but also the sectoral level (see Section 4.3). In sum, real private investments are about 7.4% higher in 2030 in the EXP scenario. This difference is slightly larger than the investments directly associated with the expansion

strategy, or, technically speaking, higher than the exogenous investment impulse fed into the model. This result is related to the accelerator principle: stronger GDP growth leads to the need for capacity expansion and, thus, additional investment demand.

The second driver for higher growth in the EXP scenario is an increase in private consumption, which is about 3.7% higher than in the NULL scenario. Notably, consumption increases despite the strain put on consumers' incomes that arise through the additional costs of renewable support. The contractive influence on households' budgets is smaller than the expansionary effect of additional income generated by higher production due to investments in renewables.

Trade is an important channel through which the expansion of renewables affects the performance of an economy. First, the substitution of imported fossil fuels in the EXP scenario translates into lower German imports. As shown in Fig. 4, imports of fossil fuels are reduced by €33 billion in 2030. The expansion of renewables, second, creates opportunities for exporting renewable energy facilities and components. In the EXP scenario, these exports amount to about €30 billion in the year 2030. Last, changes in international price relations tend to weaken German competitiveness. In the EXP scenario, this phenomenon remains, however, modest in size: only about 18% of the initial RES export impulse is offset by a price-induced decline of other exports in 2030. In effect, total exports are about 0.9% higher in 2030 in EXP compared to NULL. Likewise, overall imports are about 0.9% higher in EXP by 2030—despite diminished imports of fossil fuels. This is because the more dynamic domestic performance of the German economy increases import demand, which more than offsets the decline in fossil fuel imports. In sum, the trade balance is hardly affected.

According to our model results, the net employment effect in the EXP scenario is positive, but small in magnitude. In 2010, employment is about 43,000 persons greater compared to NULL. These initial job gains, however, decline over time, but still remain positive. Stronger economic activity and output growth related to renewable energy expansion, hence, do not translate into major employment effects. Instead, we observe a rise in labour productivity that goes along with the increase in GDP. Accelerated economic growth without a significant rise in employment – as

Table 2
Net economic effects of RES expansion in Germany in the COST scenario. Change between COST and NULL in %, employment in absolute numbers.

	2010	2020	2030
GDP	**1.3**	**1.1**	**1.1**
Private consumption	0.8	1.5	3.2
Private investments	13.5	9.9	7.5
Exports	−0.2	−0.3	−0.5
Imports	1.5	1.2	1.7
Productivity	**1.2**	**1.1**	**1.1**
Employment	**44,000**	**2,000**	**2,000**

GDP and final demand components in euros (constant prices of 2000). Productivity is calculated as GDP per person employed. Private investments without construction investments.
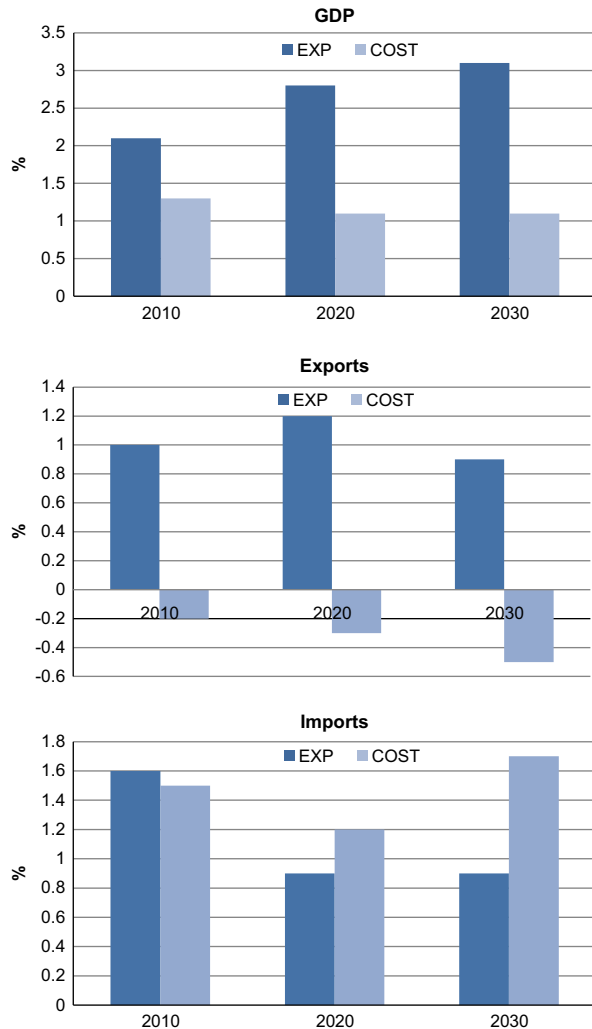
Table 3
Net economic effects of RES expansion in Germany in the FLEX scenario. Change between FLEX and NULL in %, employment in absolute numbers.

	2010	2020	2030
GDP	**2.1**	**2.8**	**3.1**
Private consumption	1.1	2.2	3.7
Private investments	13.5	10.1	7.5
Exports	0.9	1.2	0.9
Imports	1.6	0.9	0.9
Productivity	**1.9**	**2.4**	**2.4**
Employment	**72,000**	**151,000**	**263,000**

GDP and final demand components in euros (constant prices of 2000). Productivity is calculated as GDP per person employed. Private investments without construction investments.
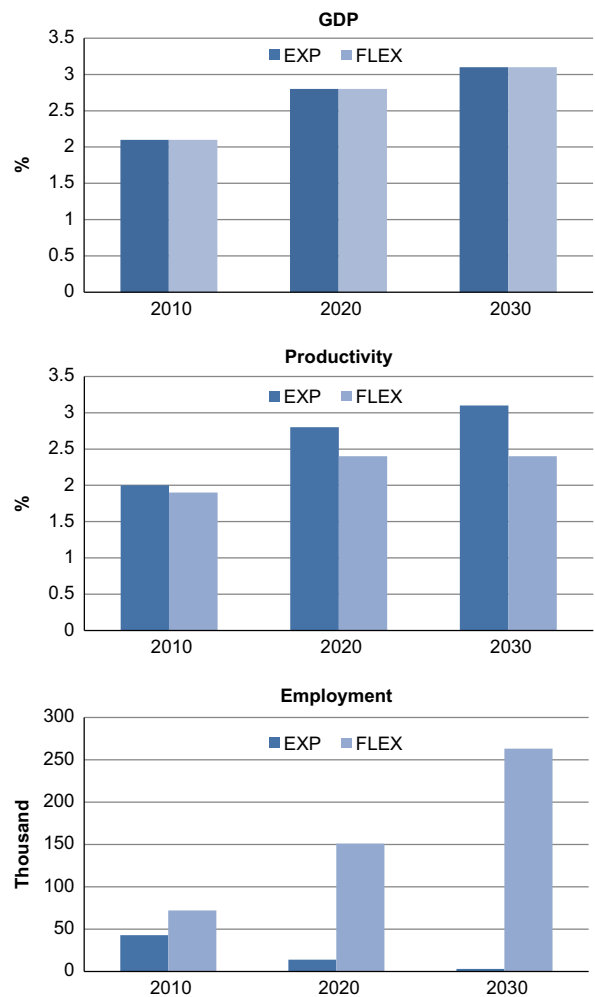

Fig. 5. GDP, exports and imports for the EXP and COST cases. Percentage deviation between the respective case and NULL.

Fig. 6. GDP, productivity and employment for the EXP and FLEX cases. Percentage deviation between the respective case and NULL.

suggested by our model outcomes – may occur in the case of previous labour hoarding. In such a situation, an increase in production reduces the underutilization of employed labour, resulting in an increase in productivity.[10] Even if this 'buffer' of hoarded labour is fully exploited, firms find many ways to increase production without hiring additional workers, i.e., to increase

productivity, particularly in situations of a mismatch between qualifications supplied and demanded.

4.2. A case with decreased international competitiveness (COST)

The scenario EXP assumes that the expansion of renewables does not affect unit costs in Germany. This appears plausible as firms active in economic sectors with strong international
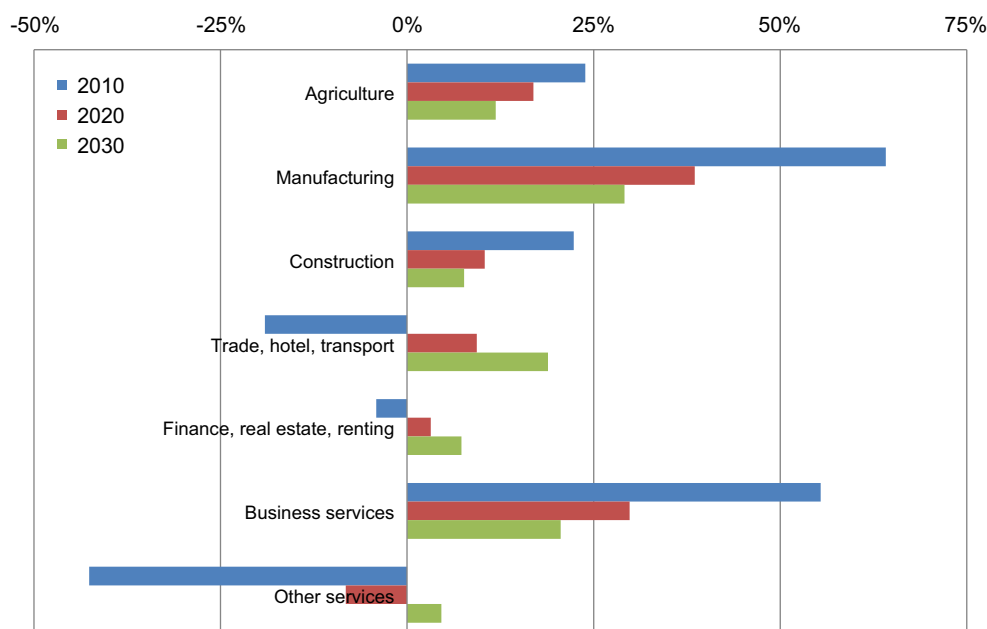
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[10] Such a phenomenon could, for instance, be observed during the recovery from the 2008 economic crisis in Germany.

Fig. 7. Sectoral distribution of employment effects for the FLEX case. Total employment effect = 100%.

competitive pressures are exempt from the burdens associated with the renewable support policies.[11] However, a price-wage spiral may nevertheless be triggered via the pass-through of higher energy costs of sectors not exposed to international competition. This may indirectly increase the costs of export-oriented industries, such that the international competitiveness of German goods and services may deteriorate. The COST sensitivity analysis depicts this case.

As displayed in Table 2, we still find a positive economic growth effect associated with the expansion of renewables. In comparison with the EXP case, however, GDP increases less. By 2030, it is 1.1% higher than in the NULL scenario. The more moderate GDP expansion is mainly related to weaker exports, which are by 0.5% lower than in NULL, although exports of renewable energy facilities and components remain the same as assumed in EXP. Imports, on the other hand, are about 1.7% higher in 2030 compared to NULL. This German trade performance is explained by an unfavourable change in relative prices, which tends to hurt the German export position and favour imports. Private consumption follows the growth in GDP and increases nearly as much as in EXP: It is approximately 3.2% higher in 2030 than if renewables are not deployed. Regarding employment, we obtain comparable results as in the EXP scenario (Fig. 5): there is a small, but positive employment effect. In COST, as in EXP, changes in GDP tend to go hand in hand with productivity changes, rather than creating employment.

4.3. A case with a flexible labour market (FLEX)

Structural characteristics of the labour market, such as the natural rate of unemployment or the pool of unemployed labour, are drivers of model outcomes, particularly for estimates of employment effects (compare [34]). In both EXP and COST, labour productivity rises in line with GDP, such that net employment effects are limited. The FLEX case is based on identical impulses as the EXP scenario, but we modify the model assumptions concerning the German labour market. The model now allows for a more flexible labour market such that employment is more responsive to additional growth of output.

Table 3 shows that GDP is by 3.1% higher than in NULL in 2030, just as in the EXP scenario. The increase of labour productivity is now smaller—it is only about 2.4% higher compared to NULL. Correspondingly, the positive stimuli from the expansion of renewables now translate into job creation: employment is by about 263,000 persons higher in 2030 than in NULL. The unemployment rate of 2030 is about 11% lower than it would be without RES expansion. Other economic indicators, such as private consumption or investment, do not change much compared to the EXP scenario. Fig. 6 compares the development of GDP, productivity and employment of the sensitivity analysis with flexible labour market conditions to those of the EXP scenario. These model outcomes underpin the conclusion that complementary labour market activation policies like retraining schemes can contribute to creating green jobs.

4.4. Sectoral results

Regarding the sectoral implications of renewable energy expansion, we find that changes in the structure of final demand have an impact on sectoral employment—even without considering future changes in input–output interactions. Fig. 7 shows the sectoral distribution of employment effects across different sectors for the FLEX case. The total employment effect adds up to 100% in each year. The manufacturing industry is the main winner, as it benefits more from RES facility manufacturing than do other sectors. There are also large positive employment effects in the business-related service industry. In contrast, employment in public and private services decreases. Over time, the differences decrease due to second-round effects. We find similar relative effects in both the EXP and the COST case. The FLEX results are presented because the absolute employment effects are much larger in FLEX compared to EXP.

5. Discussion and conclusions

In this article we examine both economy-wide and sectoral implications of renewable energy expansion in Germany. Many previous studies have concluded that increased renewable deployment has the potential for substantial positive gross economic

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[11] In their analysis on employment effects of energy efficiency policies Scott et al. [52] also assume that prices and costs are not affected as political measures are too small to induce significant effects.

effects in many regions of the world [4,54,56,58]. In contrast to such studies, we do not focus on *gross* effects, but evaluate *net* economic outcomes by applying a fully integrated global econometric model that takes account of various interrelated economic mechanisms, including trade, competitiveness, and international price effects. Our main finding is that the expansion of renewable energy in Germany has a positive net effect on economic growth. A major driver for this outcome, which is robust for different model runs, is increased investment activity.

We also find that positive net employment effects of renewable deployment are possible. This contrasts the findings of earlier model analyses by Hillebrand et al. [35] or Böhringer et al. [10], which do not consider innovation and trade effects, productivity gains as a source of additional production, or RES-related improvements of international competitiveness. It should be noted that our model takes into account all potentially 'off-setting impacts' on economic welfare mentioned by Frondel et al. [33], such as the substitution of cheaper forms of conventional energy generation and negative impacts of increasing electricity prices. Overall, we find that net employment effects are small, but positive if labour markets are rigid and additional workers cannot be easily mobilised from the pool of unemployed. In this case, additional production is made possible by an increase in productivity. In contrast, more flexible labour market conditions lead to substantial job creation. We thus conclude that net employment effects of renewable energy expansion strongly depend on prevailing labour market conditions. If a RES-based energy supply requires additional inputs of economic resources, and if the economy is already producing at its production possibilities frontier, other economic activities may be crowded out. Additional production possibilities may, however, arise via higher productivity or increased labour supply. This result hints to the importance of labour market policies as a supplement to RES expansion, for instance, in the form of measures to increase labour market participation. In any case, net job effects of renewable energy expansion are much smaller than gross employment effects.

Our disaggregated analysis indicates that renewable energy expansion also triggers sectoral restructuring, as the expansion of renewable energy results in a re-allocation of economic resources. In particular, both fixed and human capital are invested in RES technologies instead of conventional energy technologies. This underlines the need for labour market policies, in particular for additional qualification measures. This may require further research on the transformation of existing jobs, that is, changes in skill requirements and job profiles [47,57].

Last, but not least, we want to recall that the primary aim of a transition towards RES is to reduce environmental impacts and to improve the long-term security of energy supply. Our analysis suggests that these benefits can be obtained without sacrifices of income and net employment.

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